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Model fatigue: debugging Hector through climate computational aesthetics

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Abstract

In this paper, we document three computational features of the climate model Hector by translating the modalities through which the model predicts climate futures in a game engine. We build upon the computational aesthetics of M. Beatrice Fazi and Matthew Fuller (2016) and suggest additional characteristics of computation to their proposed list. We argue that these computational aesthetics are essential to climate modelling. The three features are time series, couplings and cosmograms, which are based on our practical and theoretical inquiry into Hector's computation and literacy. We develop a framework that employs two processual methods: translating the model's operations into a game engine and the conceptual as well as transdisciplinary debugging of this transfer across different computational interfaces. Through this framework, we ask: what does the process of translating while debugging Hector reveal about the computational aesthetic of the model, and how can this help inquire into its onto-epistemological imaginary? By thinking and practising through specific features of computational aesthetics, we propose a reimagining of climate computation. We introduce the model, the concept of computational aesthetics, and our research methods to describe the three features of climate computation and their influence on Hector's onto-epistemological imaginary. Finally, we discuss game engines as a site for critical experimentation with the model and the potential reconfiguration and reimagining of computational aesthetics through what we call "climate engines".

Keywords
computational aesthetics; climate engine; transdisciplinarity; debugging; cosmogram; onto-epistemological imaginary

Model Fatigue*: depuración de Hector a través de la estética computacional del clima*

Resumen
En este artículo, documentamos tres características computacionales del modelo climático Hector trasladando a un motor de juego las modalidades a través de las cuales el modelo predice los futuros climáticos. Nos basamos en la estética computacional de M. Beatrice Fazi y Matthew Fuller (2016) y sugerimos características adicionales de cálculo a la lista que proponen. Argumentamos que esta estética computacional es esencial para el modelado climático. Las tres características son series temporales, acoplamientos y cosmogramas, que se basan en nuestra investigación práctica y teórica sobre el cálculo y el conocimiento de Hector. Desarrollamos un marco que emplea dos métodos procesuales: traducir las operaciones del modelo a un motor de juego y la depuración conceptual y transdisciplinaria de esta transferencia a través de diferentes interfaces computacionales. A través de este marco, preguntamos: ¿qué revela el proceso de traducción mientras se depura Hector sobre la estética computacional del modelo, y cómo puede esto ayudar a investigar su imaginario ontoepistemológico? Al pensar y practicar a través de características específicas de la estética computacional, proponemos una reinvención del cálculo climático. Presentamos el modelo, el concepto de estética computacional y nuestros métodos de investigación para describir las tres características del cálculo climático y su influencia en el imaginario ontoepistemológico de Hector. Por último, hablamos de los motores de juego como un lugar para la experimentación crítica con el modelo y la posible reconfiguración y reimaginación de la estética computacional a través de lo que llamamos «motores climáticos».

Palabras clave
estética computacional; motor climático; transdisciplinariedad; depuración; cosmograma; imaginario epistemológico

Introduction

Hector is an open-source model available on the developer platform GitHub (Dorheim *et al*. 2025) and is described as a Reduced-Complexity Climate Model (RCM). It was developed in the US at the Pacific Northwest National Laboratory (PNNL) in 2014. This model emulates more complex climate models, such as Earth-System Models (ESMs), to assess the impact of various policies on the concentration of Carbon Dioxide (CO2) in the atmosphere and to calculate the variation in global mean temperatures (Dorheim 2024). Models like Hector aim to be "computationally efficient" and "inexpensive to run" compared to larger models, as they "introduce complexity only where warranted", while producing, where possible, simpler representations of large-scale climate processes (Hartin *et al*. 2014, 7076-7077). Reduced-complexity climate models (RCMs) play an integral role at the intersection of science, politics and policymaking (Nicholls *et al*. 2020) and are designed for contexts such as the Intergovernmental Panel on Climate Change (IPCC).

We began working with Hector after playing the planning game Half Earth Socialism, based on the eponymous book (Pendergrass & Vettese 2022), which elaborates on E.O. Wilson's proposal to protect and set aside half of the planet from human activities (2017). In HalfEarth Socialism, the player interacts with Hector by taking on the role of a world planner responsible for developing a vision for climate governance, who must balance the political forces of global governance, natural disasters, and public approval while trying to mitigate the climate crisis by implementing a range of policies. The game is designed as a deck of cards, where each card represents a policy that can be pushed forward, limited or banned within the contexts of infrastructural development for energy, climate mitigation, technological research, and social measures. The climate model Hector runs in the game's backend to test the impact of the player's decisions on CO_2 concentrations in the atmosphere and the resulting temperature variations. After testing various possible scenarios, pushing cards up and down to structure the energy mix by adding third-generation biofuel, we allocated some of our budget to invest in green hydrogen and prohibited all fossil fuel extraction. We enacted policies through our parliament to promote an eco-feminist and Fanonist curriculum while also banning air travel. Additionally, we invested in infrastructure to expand our composting facilities, leaving carbon capture without funding. These decisions led to us losing our majority in parliament and, ultimately, our positions as world planners. After being fired multiple times from the role of world planner, we began to question Hector's computational logic. When game development focused on the intersection of geopolitics, ideologies, and governance in scenario construction, we wondered whether the computational organization of the model was already shaping the way the future was described. We became curious about whether, in the game, climate scenarios are entangled in a computational framework, or if they were inherently hard-coded within growth-oriented and racial capitalism, preventing the player from imagining Earth's future otherwise (see also Pritchard *et al.* 2025).

In this paper, we recount the translation of the model Hector into a game engine as a practical and artistic approach to understanding the materiality of the model's operations and literacies. To do this, we navigate between different computational abstractions, interfaces, and visualities. The work departs from Hector's open-source script in R – a programming and visualization language – (Ihaka & Gentleman 1993) to its reprogramming into a game engine, Unreal Engine (Sweeney 1998). Multiple interfaces and representations were mobilized as visual "proxies" to troubleshoot and debug the model (Chun 2018). Some of the main interfaces used are the core mathematical equations of the models (Figure 1), a Python script (Figure 3), and the conceptual diagrams of the model architecture (Figures 5 and 6). As Jennifer Gabrys writes, "Climate change is an event that comes into view through planetary computation, where global infrastructures make it knowable". We document this translation process as a mode of inquiry into Hector's onto-epistemological imaginary. Building on Gabrys' work together with Beck's argument on the "world-making powers" of climate science and their ability to create "new political realities", we ask whose worlds are to be simulated through a model like Hector (Beck & Mahony 2018). We investigate the "world-making" capacity of Hector and how futures are constructed through the model's material infrastructure, code, architecture and visuality. We examine the recursive effect of the model's processes and imaginary by expanding from Birgit Schneider's argument on climate visualizations of scenarios as cosmological blueprints of the future (2016). We discuss the modelling practices of climate and how Hector's computational operations act as a description of a specific cosmological organization of the Earth (see also Legrand 2025), which has concrete impacts on present climate governance.

To develop a framework for a translating and debugging approach, we draw from our trans*feminist practices, where we engaged in a critical reappropriation of the technical bug reporting (Possible Bodies 2021). In this, debugging encompasses not only the technical aspects of the geocomputational model G-Plate but also an inquiry into its sociotechnical dimensions. In the arts, bugs as a creative practice have a long-standing legacy, with artists such as Rosa Menkman (2009) opening a breach into the aesthetic and conceptual flaws of specific computational systems.

Table S8: Carbon cycle equations and parameters.

$$\frac{d[CO_2]}{dt} = F_E(t) + F_O(t) + F_L(t) \quad (S20)$$

$$F_E(t) = E_{FFI}(t) - U_{DACCS}(t) \quad (S21)$$

$$F_O(t) = E_{HL}(t) - U_{HL}(t) + E_{LL}(t) - U_{LL}(t) \quad (S22)$$

$$F_L(t) = E_{LUC}(t) + Rh_d(t) + Rh_s(t) - NPP(t) - U_{LUC}(t) \quad (S23)$$

$$NPP(t) = NPP_0 \times f([CO_2](t), \beta) \times f(LUC_v(t)) \quad (S24)$$

$$f([CO_2](t), \beta) = 1 + \beta \times log\left(\frac{[CO_2](t)}{C_0}\right) \quad (S25)$$

$$f(LUC(t)_v) = \frac{C_v(t=0) - \sum_{i=0}^{t} LUC_v(t)}{C_v(t=0)} \quad (S26)$$

$$\frac{C_v}{dt} = f_{nv}NPP(t) - (f_{vd} + f_{vs})C_v(t) - f_{lv}(t)E_{LUC}(t) + f_{lv}(t)U_{LUC}(t) \quad (S27)$$

$$f_{lv}(t) = \frac{C_v(t)}{C_v(t) + C_d(t) + C_s(t)} \quad (S28)$$

$$Rh_s(t) = f_{rs}C_s(t)Q_{10}^{T_{land}(t)/10} \quad (S29)$$

$$Rh_d(t) = f_{ds}C_d(t)Q_{10}^{T_{land}(t)/10} \quad (S30)$$

$$\frac{C_d}{dt} = f_{nd}NPP(t) + f_{vd}C_v(t) - f_{ds}C_d(t) - Rh_d(t) - f_{ld}(t)E_{LUC}(t) + f_{ld}(t)U_{LUC}(t) \quad (S31)$$

$$f_{ld}(t) = \frac{C_d(t)}{C_v(t) + C_d(t) + C_s(t)} \quad (S32)$$

$$\frac{C_s}{dt} = f_{ns}NPP(t) + f_{vs}C_v(t) + f_{ds}C_d(t) - Rh_s(t) - f_{ls}(t)E_{LUC}(t) + f_{ls}(t)U_{LUC}(t) \quad (S33)$$

$$f_{ls}(t) = \frac{C_s(t)}{C_v(t) + C_d(t) + C_s(t)} \quad (S34)$$

$$\frac{C_{earth}}{dt} = U_{DACCS}(t) - E_{FFI}(t) \quad (S35)$$

$$F_i(t) = \kappa(t)\alpha(t)\Delta pCO_2(t) \quad (S36)$$

Figure 1. Core equations of Hector's carbon cycle between the land and atmosphere model components
Source: Hector's scientific literature (Dorheim 2024)

In this paper, we employ a dual methodological approach of translating and recursively debugging Hector within a game engine alongside climate scientists. We do this to make tangible the particular features of computation and their modes of onto-epistemological production, which we argue reflect the cosmological imaginary of climate computation.

As artists exploring climate computation through debugging, game engines, and transdisciplinary approaches, we aim to question the role of artistic practice in revealing other modalities of climate computation. While many artistic works focus on the aesthetics of climate and its narratives, we seek to explore the modalities of computation and its processual aesthetics. We consider the implementation of the model within the software Unreal Engine and the development of what we term a "climate engine": the transformation of climate models into world-making apparatus. Our experiments utilize the ambivalence of game engines to create tension with climate models that standardize and universalize Earth knowledge, while also serving as sites for reprogramming, rehearsing and reimagining climate computational cosmology(ies).

1. Methodology

Over the past 12 months, we developed a framework to investigate Hector, creating conversational sites through transdisciplinary and conceptual debugging of the model's operations. This framework was established with the aim of translating the model's operations into a game engine. We probed and documented the model alongside Hector's maintainer, who is responsible for its literacy, maintenance, and engagement with Hector's GitHub community. Another collaborator is a PhD holder in climatology from UC Louvain in Belgium, specializing in climate modelling. We conducted weekly sessions where we unpacked the literature, examined the model interface in R, and reprogrammed the model's operations step by step in a Python script. We shared a subfolder within Hector's repository, where we hosted and annotated a Python script to log all modifications, potential issues, or missing information. Through this iterative process with the maintainer and the climatologist, we adopted a non-linear approach, where discussions began with troubleshooting the script, leading to a critical examination of the model's modalities and imaginaries across interfaces, epistemologies, and aesthetics.

The practice of onto-epistemological debugging of the model could be qualified as a tedious and probably inefficient technological transfer. However, it has allowed us to contend with what it takes to formulate futures through Hector's infrastructure beyond the technical aspects by discussing the technopolitics of the model that are not included in its equations or literacy. It is in these "excess" stories of the debugging, its granularity and visuality, that the construction of computational aesthetics surfaced, and the cosmological imaginary of the model can be unearthed (de la Cadena 2014, 248).

To document the model's imaginary, we mobilized three features of computational aesthetics within the context of climate modelling, which emerged during the translation process. This builds on the "Ten Aspects of Computational Aesthetics" by M. Beatrice Fazi and Mathew Fuller (2016). The authors define computational aesthetics as a process inherent to the concept of computation that "does not simply represent reality but contributes to the immanent constitution of reality itself" (Fazi & Fuller 2016). More specifically, they discuss the feature of universality, which is central to Hector's computation as a generalized mode of understanding the changing climate, as the model functions as a "one cell" model with low spatiotemporal resolution, where Earth's geophysical state is reduced to a single biome. Another proposed feature is the limits of computation, which are conceptually fundamental to computation; Hector's architecture is designed to overcome this limitation by essentializing the operations of more complex climate systems. This, in turn, introduces other forms of constraints: the limitations of climate imaginaries.

In their paper, Fazi and Fuller establish a framework to "proliferate and recognise further modes of existence for the computational" (Fazi & Fuller 2016). We bring the framework of computational aesthetics to climate computation to document the internal (implicit or explicit) processes, conditions, expressions and recursivity through which climate predictions occur and are experienced.

We propose three additional features of climate computation: **1)** *Time series*: the linear construction of historical and future climate data against time resolution, **2)** *Coupling*: the interlacing of models, modes of instrumentation and interfaces to scale the spatiotemporal modalities of climate prediction, and **3)** *Cosmogram*: the conceptual architecture of climate infrastructure as computational modalities to produce the conditions of Earth's future.

With these three features, we aim to highlight the onto-epistemological productions of climate computation. Specifically, we argue that models like Hector formulate the future of Earth by maintaining a business-as-usual imaginary, a growth-driven, Eurocentric, and technocratic carbon cosmology. Lastly, we discuss the project *Model Fatigue*, which recounts the development of Hector as a climate engine, where we attempt to reprogram, rehearse and reimagine the model computational aesthetics through game practices.

2. Features of climate computational aesthetics

The three features discussed below are not a comprehensive assessment of the model, but rather a selected set of characteristics relevant to both debugging the operations and translating the model into a game engine.

2.1. Time series

Time series are fundamental to climate computational logic and define the spatiotemporal mode through which Hector forecasts future climate change. In scientific terms, time series are a sample of data values modelled against time, where for each point in time t(i), there is a corresponding data point x(i), and where the average interval between each step of a time series determines the model's time resolution (Mudelsee 2019, 310). Time series are utilized to evaluate systematic changes in the spatial mean over a period. Since the 19th century, the climate modelling aspect of time series has entered the public sphere through curves like the "hockey stick" (Mudelsee 2019, 310) or the Shared Socioeconomic Pathways (SSP) (Figure 2). The SSP graph is a visual representation of the time series, where temperature is plotted against time, illustrating variations in temperature between 1745 and 2300, as shown in Figure 2. When the curve reaches the present, it splits into different pathways, visualizing the impact of various climate scenarios (SSP) on temperature changes. The graph condenses 555 years from the past to the future into a single curve; this computational timeframe serves as a baseline for measuring global temperature and setting targets for climate mitigation, such as the 2 °C rise above pre-industrial levels established by the IPCC.

While debugging Hector's Python script, we compared Hector's time series (Figure 3); Guillemette calculated manually (with pen and paper) through the core equations of the model while running the Python script in parallel to compare results from both methods. Moving between analogue and digital, each step of the time series becomes experienceable, where the only way to predict climate is to start at the beginning of recorded climate change in 1745. Climate predictions from Hector's computation result from the cumulative carbon differential at each time step. Through the effort of running the model manually, we experienced the temporal process in which the climate's past, present, and future operate on a single linear plane of cumulative carbon flux. Hector simulates climate by excavating the model-memory of climate – recorded data since 1745 – to project Earth's future.

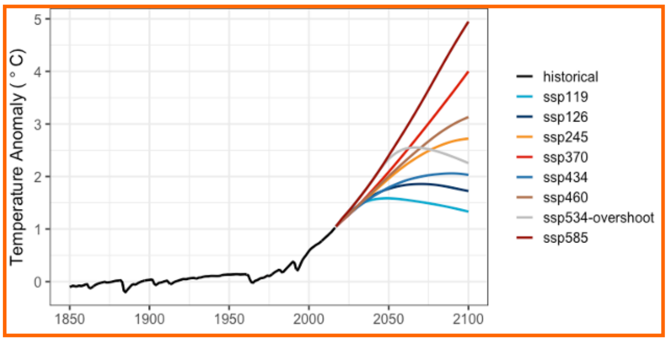

Figure 2. The Shared Socioeconomic Pathways (SSP) graph
Source: Hector's repository on GitHub (last accessed April 2025)

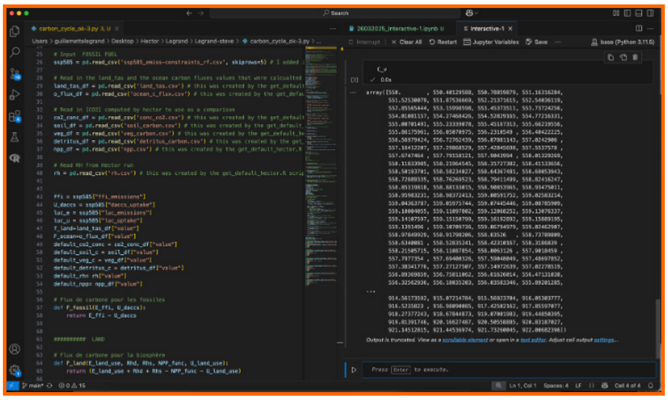

Figure 3. Hector's Python script in Visual Studio Code, an integrated development environment. At the bottom right of the image is the time series of the vegetation carbon pool
Source: own creation

The construction of time and its computational aesthetic within the model was discussed in greater detail during one of the debugging sessions with the climatologist while running the model's spin-up phase. During this stage, all model components are repeatedly called and run "to equilibrium in an ahistorical, perturbation-free mode" to ensure their stability before starting the main simulation (Hartin *et al.* 2014, 7080). The idea of the model being "ahistorical" also means that it can become "historical" when used in other computational processes. Hector's history begins in 1745, a date debated among scientists, as it is considered the tipping point at which human activities' impact on Earth's climate can be measured. The year 1745 marks the transition into the so-called industrialized era, which conveys a specific reading of world history: one characterized by the industrialization of imperialist nations. Hector's temporality is encoded into a Eurocentric historical reality through the computational aesthetic of time series. In this temporal imaginary, past, present, and future are scaled and averaged across Earth via the model operations, further distancing it from Earth's reality and the "located accountability" of climate change (Suchman 2002).

2. Coupling

Coupling is at the core of climate computational infrastructure. It enables interlacing between different models, modes of instrumentation, and interfaces to achieve the complexity, scale, and temporal resolution necessary to represent and project climate (Mahadevan *et al.* 2020). Coupling involves multiple modalities of interlacing, including interpolation and remapping, which are used to overcome the complexity and material limitations of computational infrastructure, such as power, speed, or storage (Mahadevan *et al.*, 2020). Coupled models are "linked computer models" that combine the practices and instruments of many disciplines, including oceanography, agriculture, policymaking and demography, in a single, "many-faceted simulation" (Edwards 2010, 16). Coupling in climate computation has been promoted by politico-scientific initiatives, such as the Intergovernmental Panel on Climate Change (IPCC), to harmonize climate practices, data, and models, thereby enabling global-scale climate governance (Edwards 2010, 16).

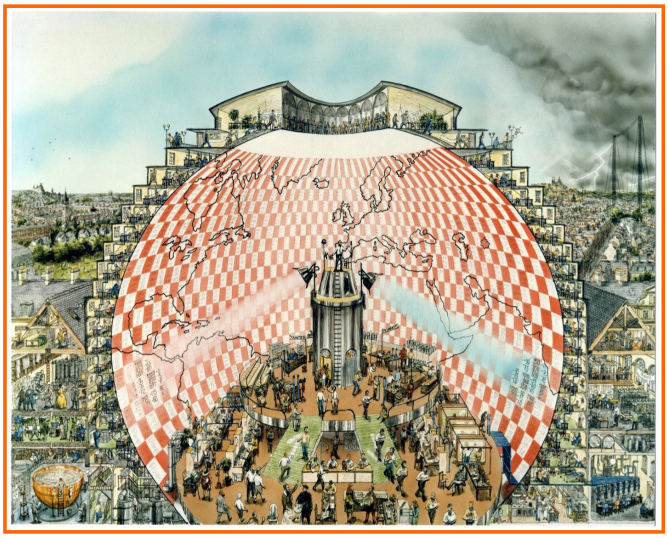

Figure 4. "Weather Forecasting Factory" by Stephen Conlin, 1986. Based on the description in *Weather Prediction by Numerical Process*
Source: L.F. Richardson, Cambridge University Press, 1922

The premise of computational and infrastructural coupling is best illustrated by Lewis Richardson's speculative work "forecast-factory"

(Figure 4), the first concept of global climate computation. The "forecast-factory", or what theoretician Paul Edwards has called a "numerical orchestra for global weather prediction" (Edwards 2010, 96-97), is envisioned as a vast theatre filled with 64,000 human-computers. The theatre's walls are made of a map of the globe divided by a grid, with each cell containing a human-computer calculating a single climate equation or part of it based on the specific geographic area in which they are located. Each human-computer is directed by a "conductor" at the centre of the theatre who acts as the computational coupler. Richardson's concept of climate computation remains a relevant metaphor for computational coupling. It may be more precise than common metaphors that focus on "mostly individual" features like neural networks or the brain, as Edwards notes (Edwards 2010, 96). Instead, the concept of the "forecast factory" reflects the embodiment of coupling infrastructure of calculations, geographies, time steps and outputs to overcome the physical limits of computation. In climate modelling, particularly with large-scale models such as Earth-System Models (ESMs), coupling occurs at two main computational levels: through the depth of the Earth, from the atmosphere to the deep ocean, and across the surface of the Earth, connecting different climate models and practices across nations.

Hector is the carbon cycle module of the more complex scenario model GCAM (Global Change Assessment Model), developed by the same laboratory (Calvin *et al.* 2019). The scenarios in Hector are built around the relationship between carbon emissions and uptakes – environmentally or technologically – and are calculated through the coupling of various data points, including information from environmental sensing instruments, as well as projections of possible geopolitical, socioeconomic, and demographic data to assess the future of climate. When we downloaded Hector from GitHub, the default shared socioeconomic scenarios (SSP) were based on those promoted by the IPCC. These scenarios, which originate from more complex coupled models like GCAM, are compiled in an Excel file as coupled numerical values. Considering the computational aesthetics feature of coupling in this file, we see how imaginaries from technosciences intersect with those from politics and economics: the column "ffi_emissions" (Fossil fuel and industrial emissions) sits beside "luc_uptake" (Land use change) and "daccs_uptake" (Direct Air Carbon Capture and Sequestration). We argue that coupling processes are more than technical interlacing of model components. Through the reconstruction or regridding that occurs between models and interfaces, these processes invoke a deeper and more tacit coupling – one involving disciplinary, epistemological, and aesthetic interoperation.

3. Cosmogram

The term cosmogram is not used in scientific literature; what we are referring to is what is described in Hector's repository as a "conceptual diagram" or, in other contexts, an abstraction of the model architecture. We build on Birgit Schneider's approach to rename this form of representation, such as Figures 5 and 6, as cosmograms to acknowledge the cosmological meaning-making of organizing Earth as a system through climate computation (Schneider 2016). Cosmograms often refer to a prescientific practice of representing how a specific culture envisions the organization of its relationship to the Earth and the Cosmos. We mobilize this term in the context of climate science to inquire into the onto-epistemological production of climate models, such as Hector, that go beyond predicting temperature change but describe a specific organization and imaginary of Earth. As a feature of computational aesthetics, cosmograms point to the condition for cosmological productions within the computational event itself. We argue that the cosmogram is an integral part of climate computation and its literacy as it oscillates between an apparatus of control enclosing meaning and an instrument for speculation of climate futures (Benqué 2020, drawing from Leeb 2017).

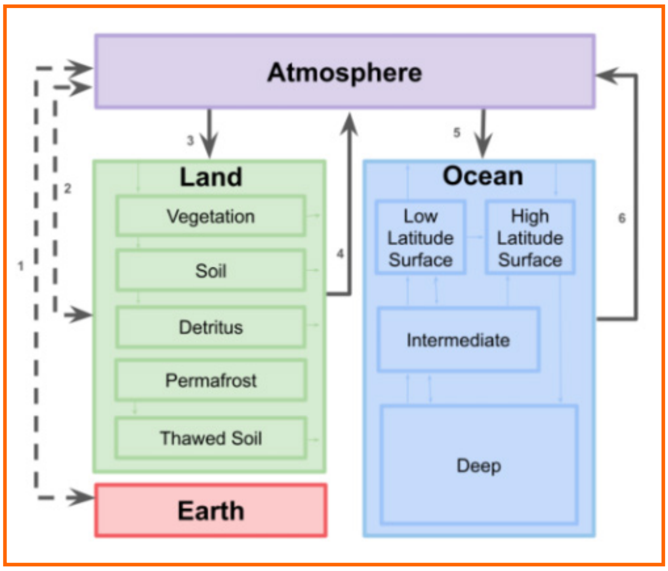

Figure 5. Conceptual diagram of Hector's model architecture
Source: Hector's scientific literature (Dorheim 2024)

In Hector, the depiction of the model architecture as a conceptual diagram (Figure 5) illustrates Earth's division into a system of subenvironments. The general structure of climate models functions by partitioning the Earth into these subenvironments, represented through different equations within "boxes". In Hector's architecture diagram, the main boxes are labelled "Atmosphere", "Land", "Ocean", and "Earth", with arrows indicating the carbon cycles between them. This compartmentalized system aims to emulate Earth as a volumetric and interconnected whole, enabling it to predict future climate conditions. Hector's cosmogram acts as a processual representation that reveals more about the computational relationships among the different model components than the components themselves. The arrow signifies the flow of carbon across these environmental boxes. During debugging, we frequently referred to Hector's conceptual diagram to spatialize the model's operations and to aid in navigating between sites for representation and projection, in collaboration with the maintainer and the climatologist. Through the iterative process involving the different computational spaces, the literature, the code, and the diagrams, the path of the carbon flow between boxes emerged as a cosmological aesthetic feature of Earth. This feature simplifies the description of Earth, which could be defined as a carbon cosmology, to a climate imaginary where carbon is a unit managed and traded to sustain a business-as-usual world (O'Lear 2016). We interpret the cosmogram as an approach that points to the limitations of climate modelling as a mode of inquiry into Earth and as an artistic practice for other imaginaries of Earth's future.

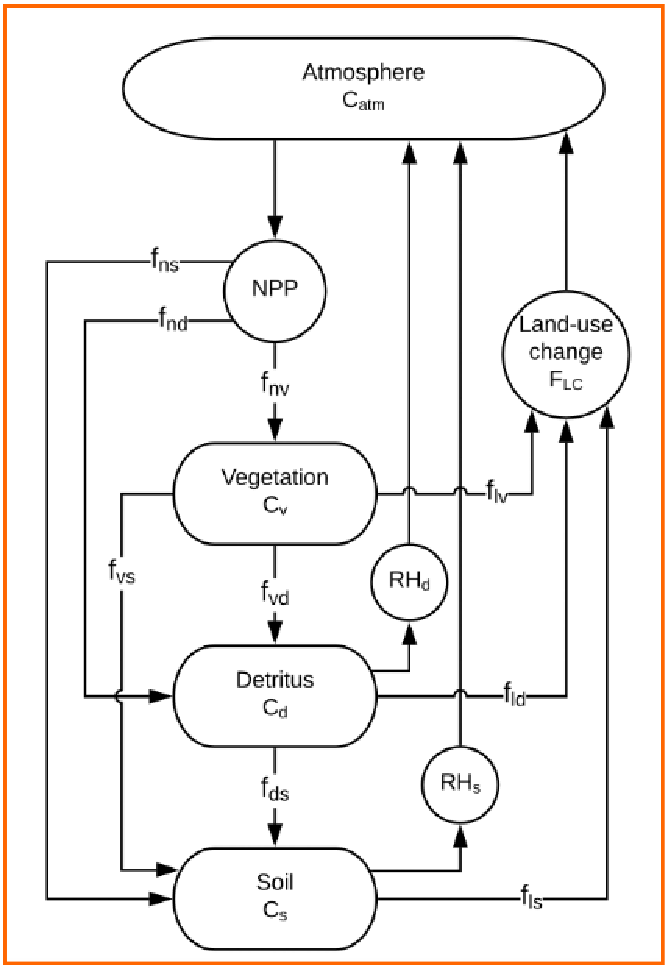

Figure 6. Conceptual diagram of Hector's carbon cycle architecture between the land and atmosphere. Source: Hector's repository on GitHub. [Accessed: April 2025]

3. Climate engine: reprogramming, rehearsing and reimagining climate computation in game engines

The three proposed features of computational aesthetics emerged during the reconstruction of Hector within a game engine. Time series, coupling, and cosmogram are essential to the model's processuality through which Hector constructs the conditions for Earth's future. Implemented in Unreal Engine, Hector shifts from functioning as a model to becoming an engine, moving from programming to blueprinting, from modelling to world-building, in a progression towards what we have called a "climate engine". The term "engine" has historically referred to both a tool and a weapon, highlighting the ambivalence in the history and development of game engines, which serve dual purposes in simulation for warfare and the gaming (entertainment) industry (Pias 2017, 12). In climate science, the term "climate engine" is already used in projects such as the European framework and the Digital Twin Engine, where digital replicas of Earth enable high-speed climate predictions and large-scale simulations through compact, user-friendly and gamified dashboards (utilizing an AI large language model). This technovisual regime configures climate infrastructure at the intersection of scientific research, climate governance, game simulation, and Big Tech. With the concept of "climate engines", we redefine a space that is distinct from creating games about climate or simulating climate within a game engine. Instead, we seek to reprogram, rehearse, and reimagine climate modelling infrastructure through its computational aesthetics.

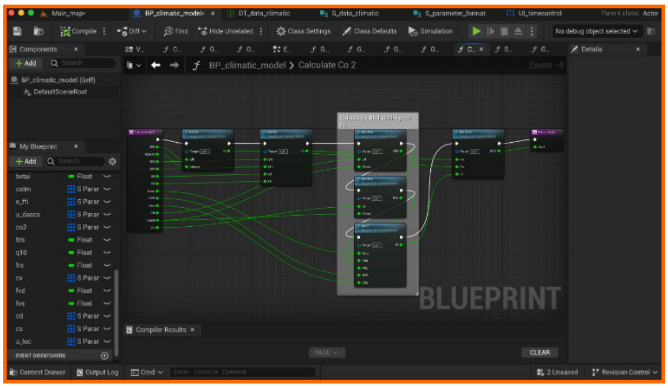

Figure 7. Blueprint Visual Scripting interface in Unreal Engine showing Hector's equations reprogrammed in the engine
Source: own creation

3.1. Reprogramming

Unreal Engine employs a node-based, "visual" programming language called Blueprint Visual Scripting. Each programming node has the potential to be spatialized and become a navigational map of a world. In this form, Hector is no longer a one-cell-world simulation, where Earth is reduced to a single global biome and climate events occur once a year. Instead, the climate engine is designed to transform Hector into a spatial environment by assigning cartographic coordinates to its model operations and outputs. In Blueprint Visual Scripting (Figure 7), we work through its node-based interface by connecting nodes of events, functions, and variables to configure Hector's computational aesthetic features. We reprogram Hector's core equations and give them the motion of an engine, enabling the configuration of possible processual worlds. In Unreal Engine, Hector's conceptual diagram or cosmogram (as previously discussed) aligns with built-in components reminiscent of climate models' architecture: a meshed terrain, a "dynamic sky", and an "ocean box". This parallel exemplifies the entanglement of climate science and game engines within their processual aesthetics.

3.2. Rehearsing

In the artistic project *Model Fatigue* we create a game world to interface with Hector's climate engine by turning Hector's representative visual expression – the SSP graph (Figure 2) – into a navigable space. The graph becomes a maze of cave formations that reimagine the spatiotemporal resolution of the model. Within the game world, the three features we proposed in the previous section are rehearsed in Unreal Engine. We explore different experiences of climate temporality by spatializing Hector's time series. Each yearly time step is converted into spatial coordinates. By reconfiguring the climate engine blueprint (Figure 7), we explore other possible cosmograms through experimentation with the entanglement of climate engine architecture and the creation of game worlds. The coupling of the climate engine is rehearsed through negotiation with the confluence and friction that occur between game architecture, processual aesthetics, and the participation of an audience.

Here, we specifically refer to *rehearsing* as it is taken up in grassroots organizing and internationalist imaginaries, as discussed by Ruth Wilson Gilmore (2022), to consider how rehearsing different experiences of climate temporality engages in new practices of organizing collectively the materialization of climate imaginaries.

3.3. Reimagining

In *Model Fatigue*, the map of the world spatializes the shared socioeconomic pathways (SSP) and their related scenarios as a cave maze with multiple routes, entries and exits. Here, we use game technology to materialize the constraints, determinacy, and uncertainty inherent in the model's ability to predict futures through the physical limitations of the game world. We shift the visuality of the climate future from a distant omniscient viewpoint – a graph averaging the entire world over centuries – to a traversed and experienceable space. It is important to note that game worlds operate within their own processual limits just as Hector does. In *Model Fatigue*, we develop methods of engaging with an audience where participants can navigate through the maze and attempt to find themselves both spatially and cosmologically, based on the retelling of the Shared Socioeconomic Pathways (SSP) that are embodied through the cave design.

Mazes are a recurring architectural element in game design, which I see as particularly relevant to climate modelling practices and the three features of climate computation. The feature time series becomes non-linear and is reimagined as a series of coexisting futures that can unravel simultaneously based on the player's decisions through the maze. The graphic quality of the maze is reminiscent of the origin of graph theory: if the player's route through the world is materialized as a line (like Ariadne's thread in Greek mythology), the manifested figure would be comparable to an "edge-weighted graph" (Pias 2017, 172). Thinking of the maze as a graph (and vice versa) enables us to think of participation in Hector's climate engine as a site for the coupling of possible cosmological and computational aesthetics of climate futures. Finally, the maze as a programmable architecture, an aesthetic, and an imaginary holds the possibility of re/de/configuration for the production of other more liberatory cosmograms that may have the complexity, plurality and radicality necessary to reimagine pathways and abolition geographies (Gilmore 2022) that diverge from Hector's business-as-usual and carbon cosmology.

Conclusion

Through our experimentation with Hector, we documented three computational aesthetic features that emerged during the debugging process of the model. Time series, coupling, and cosmogram express the modalities through which the model formulates and operates climate futures. We have argued that these features define the limitations of climate modelling while also being a modality for reprogramming, rehearsing, and reimagining climate computation. As artists inquiring into climate modelling practices, we believe that the modalities of climate infrastructure should be reconsidered as cosmological practices. By acknowledging this dimension, we propose that not only climate scientists and game designers have a role to play in the production of new aesthetics of climate imaginaries, but artists, designers, maintainers, and communities also rehearse pathways for reimagining how and what climate infrastructure matters to Earth. In an attempt to erode the hegemony and linearity of the business-as-usual techno-imaginary, we aim to facilitate the coexistence of other interoperable computational aesthetics and their cosmological imaginaries.

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